Behaviour of a highly pressurised tank of GH2 submitted to a thermal or mechanical impact

Jacques Chaineaux, C. Devillers, Pierre Serre-Combe

BEHAVIOUR OF A HIGHLY PRESSURISED TANK OF GH_2, SUBMITTED TO A THERMAL OR MECHANICAL IMPACT

J. CHAINEAUX[1], C. DEVILLERS[2], P. SERRE-COMBE[3]

1. INTRODUCTION

Safety is one of the concerns which may limit a fast and large increase in the use of GH_2 as a fuel for engines in the future.

Furthermore, for a given autonomy of a vehicle, the choice of a storage pressure of several hundreds of bars will significantly reduce the volume of the necessary tank(s). Whatever this pressure and whatever the volume of the tank(s), the storage system must be designed in such a way that the consequences of an accident, in which this system would be submitted to a thermal or mechanical impact, would be as low as possible.

Experimental work, co-funded by the EU and monitored by the Joint Research Center at Ispra site (I), was carried out in collaboration with INERIS, AIR LIQUIDE and CEA, in order to :

- define a GH_2 storage system likely to equip a H_2-fueled road vehicle,
- have it built,
- study its behaviour, when it is highly pressurised (700 bar) and submitted to a thermal or mechanical impact likely to occur in a road accident.

2. DESCRIPTION OF THE HIGHLY PRESSURISED GH_2 STORAGE SYSTEM

A real storage system may be composed of a set of several identical tanks, each one being equipped with the same safety devices. The components of the storage system which were built for the need of this work, were the following :

- one cylindrical composite 9 dm^3 cylinder, made of an aluminium liner, wired with carbon fibre impregnated by an epoxy resin and having a service pressure Ps = 700 bar (photo 1) ; this cylinder was manufactured by COMPOSITE AQUITAINES[4],
- one flow limiter (0,35 mm diameter hole), one thermal fuse and one isolating valve as safety devices. The diameter of the flow limiter was defined in such a way that, for a minimum storage pressure of 40 bar, the hydrogen mass flow would be 0,23 g/s, which is the minimum flow needed by the engine. The thermal fuse opens at 80°C. These safety devices have been fitted to the pipe supplying hydrogen from the gas cylinder to the engine, according to the diagram in Figure 1.

3. MEASUREMENT OF THE CONCENTRATION FIELD RESULTING FROM A LEAK

In case of the rupture of this pipe, there would be a leak of hydrogen, through the flow limiter. Such a rupture has been simulated for a storage pressure of 700 bar and the concentration field, generated by the discharge of hydrogen into air, as a free jet (without obstacles), has been measured.

The theory of high speed jets discharged into free air indicates that :

- because of the turbulence of the jet, hydrogen rapidly mixes with ambient air, generating a concentration field,

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[1] INERIS, B.P. n° 2, 60550 Verneuil-en-Halatte
[2] AIR LIQUIDE, DTA, BP n° 15, 38360 Sassenage
[3] CEA/CEREM, 17 rue des Martyrs, 38054 Grenoble Cedex
[4] COMPOSITES AQUITAINE, 19 route de Lacanau, 33160 Salaunes Cedex

- this concentration field is such that 3 zones can be distinguished : zone 1 which includes the outlet, where the hydrogen concentration is higher than the upper explosivity limit (UEL= 75 % vol.), zone 2 where the hydrogen concentration is lower than the lower explosivity limit (LEL = 4 % vol) and zone 3 in which the hydrogen concentration is between LEL and UEL. In zone 3, the mixture is explosive (cf. scheme on Figure 2),
- the volume of zone 3 depends only on the diameter of the outlet and on the instantaneous hydrogen pressure in the bottle,
- this volume continously decreases as the hydrogen pressure decreases ; it is maximum when the hydrogen pressure is maximum, i.e. 700 bar.

Six hydrogen sensors have been placed on the jet axis, at different distances x from the outlet of the flow limiter, in order to measure, at the beginning of the discharge, the maximum hydrogen concentration cmax. These sensors, in house designed and fabrication, have a short response time, lower than one second.

The variation of the hydrogen concentration measured by each sensor at the beginning of the discharge, has been given previously (1). More detailed results about the characterisation of the concentration field resulting from jet discharges have been given in (2).

Figure 3 shows that the variation of ($1/c_{max}$) as a function of x is linear. This result corresponds to an hyperbolic decrease of c_{max} along the jet axis. Moreover, it can be seen that c_{max} is equal to LEL for x =1,9 m. So, at the beginning of the discharge, the volume of the explosive zone (3) is maximum and can be evaluated to be 20 dm^3.

4. THERMAL AND MECHANICAL IMPACT TESTS

4.1. Definition

Different information has been drawn from :

- accidental data sets,
- French or foreign standards and regulations, concerning the storage systems for other gaseous fuels, such as natural gas,
- proceedings of hydrogen symposia.

This information has been used in order to define thermal or mechanical impact tests to simulate the real impacts which the GH_2 storage system of a vehicle is likely to sustain in a road accident.

Table 1 gathers the main features of the 2 thermal impact tests and the 4 mechanical impact tests which have been carried out.

Test number	Nature and initial pressure of the gas inside the gas cylinder (bar)	Impact type	Main features of the impact
1	Hydrogen -700	Thermal	Behaviour when submitted to a burning jet
2	Hydrogen -700		Behaviour when submitted to an hydrocarbon pool fire
3	Hydrogen -700	Mechanical	Rupture by detonating cord
4	Hydrogen -600		Behaviour when submitted to a gun bullet
5	Without any gas, half-filled with water		Fall test (+ hydraulic rupture)
6	Nitrogen - 700		Crash test (+hydraulic rupture)

TABLE 1 : Definition of the impact tests carried out

For the tests 1 to 4, the gas cylinder was put inside a wire fenced cubical enclosure (side length : 4 m), the walls of which have been designed to stop the missiles resulting from the bursting of the gas cylinder (photo 2).

4.2. Description and results of the tests

4.2.1. Test n°1

The behaviour of a gas cylinder (target gas cylinder) was tested when its wall is impinged by a jet fire, discharged from the outlet of the open thermal fuse of a nearby bottle (source gas cylinder).

The pressure inside the target gas cylinder increased gradually for a little less than 3 minutes, until the gas cylinder bursted, producing about 15 variously sized fragments.

The burning jet impinged the gas cylinder close to its bottom and far from its thermal fuse ; thus, because it stayed closed, the fuse was not able to prevent gas cylinder from bursting.

During the burst, a large fraction of the hydrogen mixed with air and burned.

4.2.2. Test n°2

The behaviour of a gas cylinder was tested by submitted it to the flames of an hydrocarbon pool fire. Unlike test n°1, the thermal fuse opened within less than 2 minutes and the gas cylinder totally emptied as a burning jet, within less than 8 minutes and without bursting.

4.2.3. Test n°3

A detonating cord was placed around a gas cylinder which was then pressurised with hydrogen up to 700 bar. When the cord was ignited, the gas cylinder burst in two fragments and the consecutive phenomena were :

- the projection of the fragments (initial speed close to 100 m/s),
- the production of an aerial pressure wave,
- the mixing of hydrogen with air and the ignition of the hydrogen-air mixture, as a fireball (photo n°3).

From the maximum aerial overpressure, the effects can be considered as equivalent to those produced by the detonation of 450 g of TNT.

The main part of the released energy comes from the expansion of the initially pressurised hydrogen and represents a TNT equivalent of 300 g. A secondary part of the released energy comes from the explosive contained in the detonating cord and it represents a TNT equivalent of 110 g.

It appears that the TNT equivalent of the released energy is a little smaller than the one deduced from the pressure effects. So, it can be considered that the energy released by the combustion of hydrogen has only a weak TNT equivalent (some tens of g). This result is confirmed by the fact that on the video-film, the fireball has a weak expansion. Moreover, a TNT equivalent of some tens of g signifies that the ratio of the mass of hydrogen which has exploded to the total mass of hydrogen stored in the bottle is lower than 1 %.

Concerning the thermal effects, the combustion of hydrogen has been so rapid (duration < 1 second) that with a heat flux sensor having a standard response time, no heat flux was measured.

The contribution of hydrogen to the mechanical and thermal effects produced during test n°3 was weak but, without any exhaustive study of the influence of each relevant parameter upon this result, it should not be considered as a general rule.

4.2.4. Test n°4

A hydrogen-pressurised cylinder was submitted to the impact of a gun bullet, shot at point-blank range and having an initial speed of about 850 m/s. The angle between the shooting axis and the cylinder axis was 45° and the impact zone was at the bottom of the bottle.

The bullet has passed trough the cylinder, which did not burst (photo n°4). Hydrogen discharged through both holes as two jets, but did not ignite.

4.2.5. Test n°5

A gas cylinder was half-filled with water and dropped from a height of 14 m, over a concrete slab (from such a height, the speed of the bottle when it touches the ground is close to 60 km/h). Then, a hydraulic rupture test was done : the cylinder rupture started at its bottom, which was the impact zone, for a pressure equal to 1000 bar. This figure is much lower than the normal rupture pressure, 1750 bar, and it can be concluded that the fall test strongly modified the mechanical characteristics of the cylinder bottom (photo 5).

4.2.6. Test n°6

Test n°6 was a crash car simulation : the cylinder was fixed horizontally on to a heavy concrete block, at such a height that it could be impacted upon by the bumper of a car crashing into the block. It was then pressurised by nitrogen under 700 bar. The car was launched by an air-gun and, at the crash time whose speed was 65 km/h and its kinetic energy was 144 kJ. The crash damaged the cylinder wall (photo 6), but the cylinder did not burst.

A hydraulic rupture test was done after the crash : the cylinder rupture started at its cylindrical part, where the impact had damaged it, but the rupture occurred for a pressure of 1700 bar, which is close to the normal rupture pressure : the crash test did not significantly modify the mechanical strength of the cylinder.

5. CONCLUSION

The behaviour of a highly pressurised (700 bar) GH_2 composite gas cylinder was experimentally studied, by submitting it to different thermal or mechanical impacts simulating those of a car crash. The cylinder was equipped with a thermal fuse (80°C opening temperature) and a flow limiter (0,35 mm in diameter).

The main results of the 6 tests performed are the following :

- the maximum length and volume of the explosive hydrogen-air mixture generated in the case of a leak discharged in free air through the flow limiter are respectively 1,9 m and 20 dm^3.
- the thermal fuse cannot prevent the gas cylinder from bursting, if the impinging jet flame coming from a nearby cylinder is too far from the fuse,
- when a cylinder bursts, the main part of the released energy comes from the expansion of hydrogen ; moreover, hydrogen mixes very rapidly with air and burns in a fireball. However, compared to the mechanical effects of the expansion, it has been shown that the contribution of hydrogen combustion was small. Finally, the thermal effects were negligible because the duration of the fireball was very short, less than 1 second.

6. BIBLIOGRAPHY

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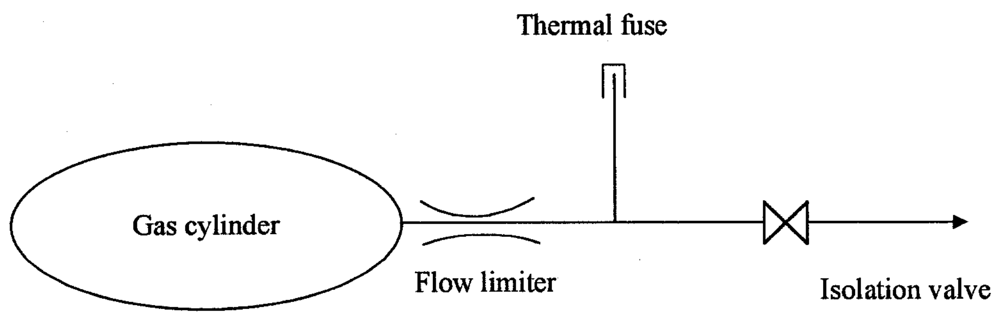


Figure 1 : Diagram of the gas cylinder, equipped with a thermal fuse, a flow limiter and an isolation valve

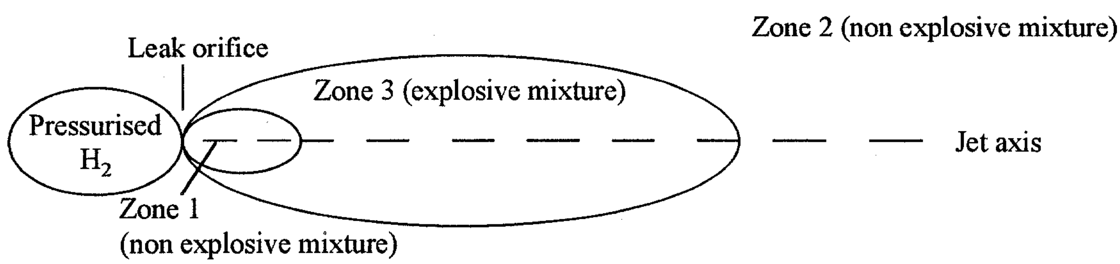


Figure 2 : Diagram of the different hydrogen-air mixtures, explosive or not, which are generated by the discharge of hydrogen into air, as a turbulent high speed jet

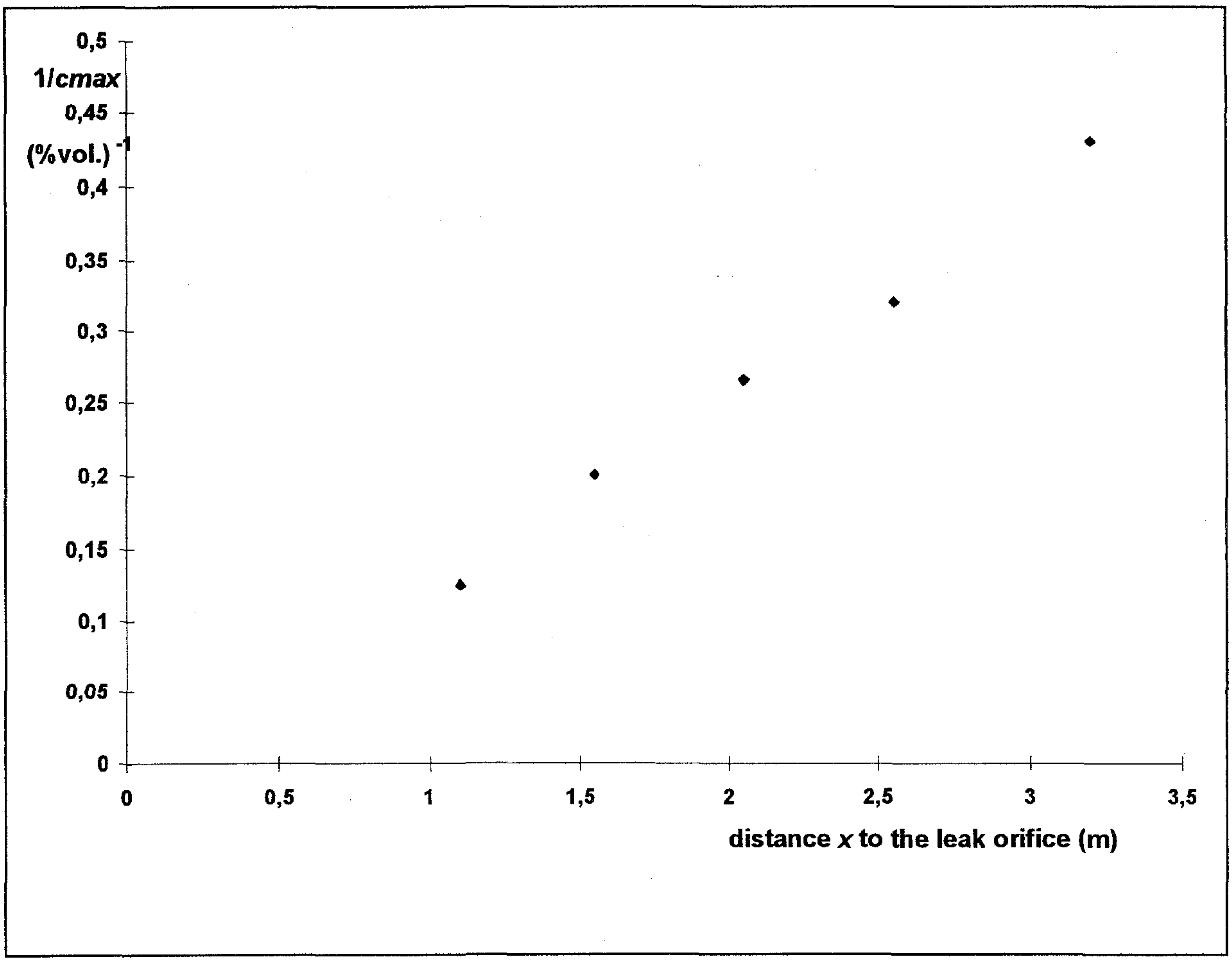


*Figure 3 : Variation of the inverse of the hydrogen concentration (1/*cmax*), measured by a sensor on the jet axis at the beginning of a leak, as a function of the distance* x *between the leak orifice and the sensor*

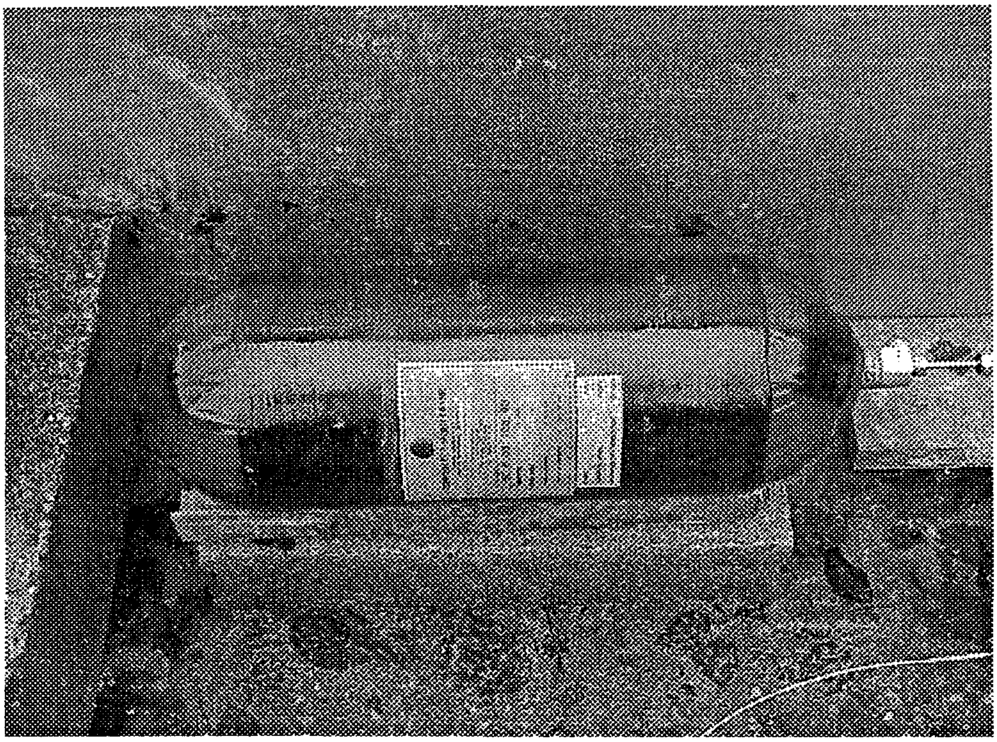


Photo 1 : 9 dm^3 composite gas cylinder, equipped with a thermal fuse and a flow limiter

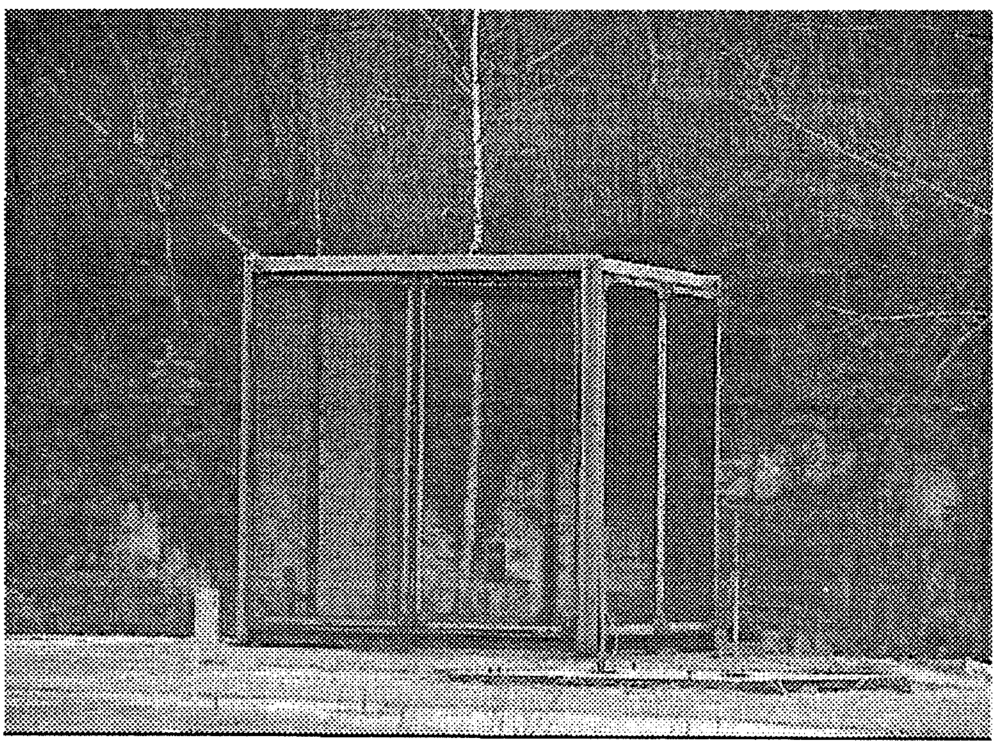


Photo 2 : Wire fenced enclosure, used for INERIS tests

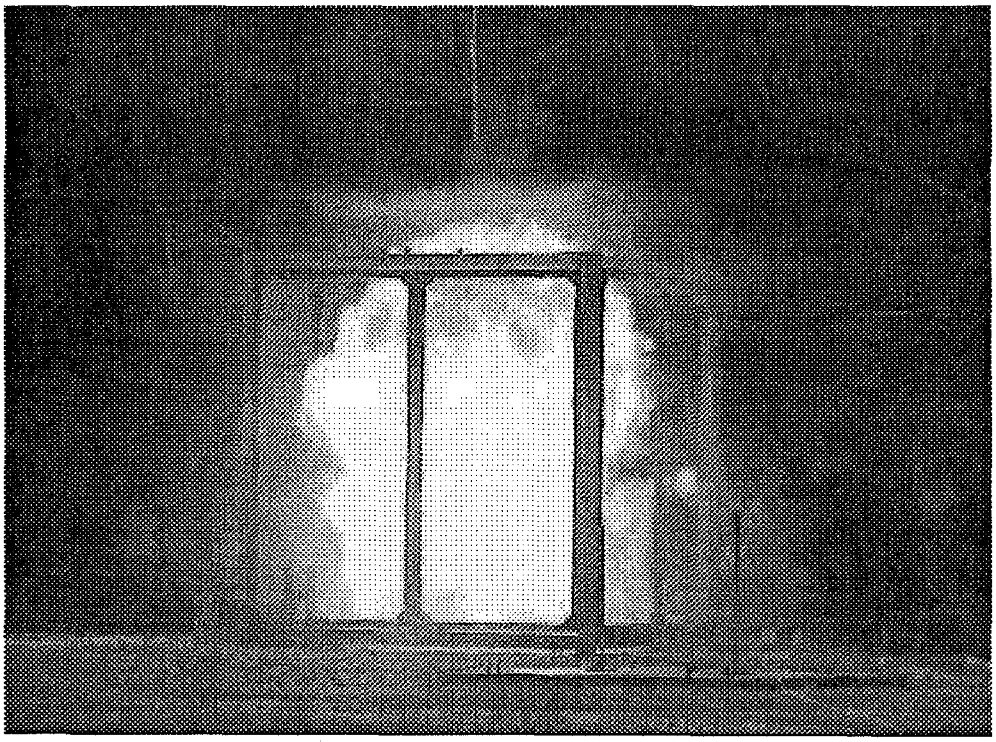


Photo 3 : Fireball produced by the ignition of the hydrogen-air mixture, generated during test n°3

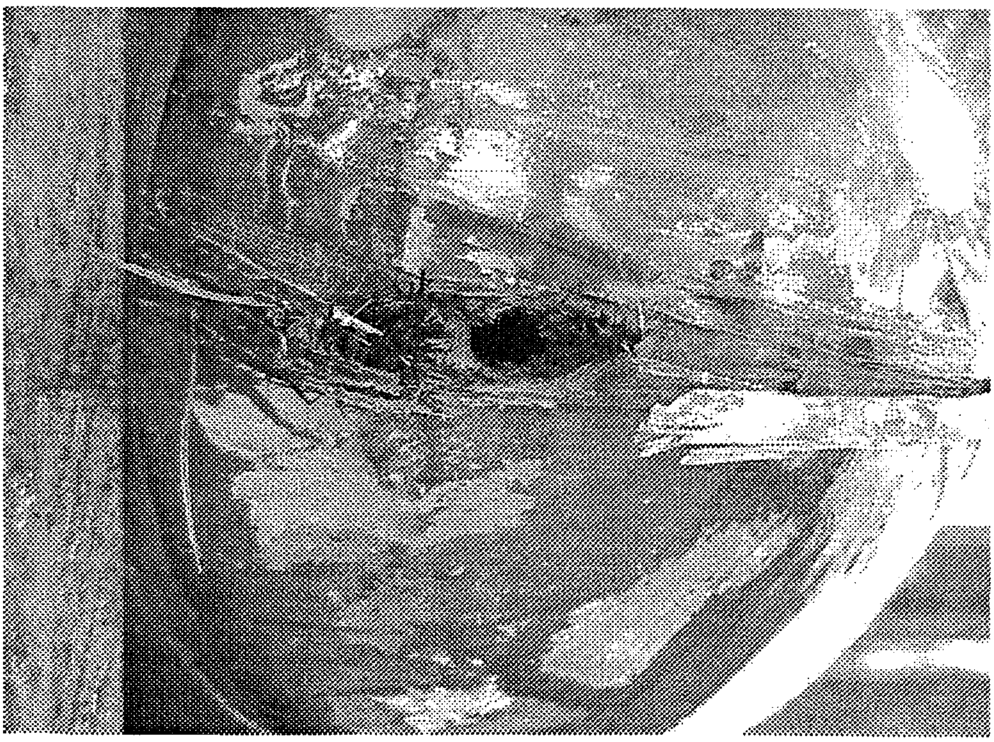
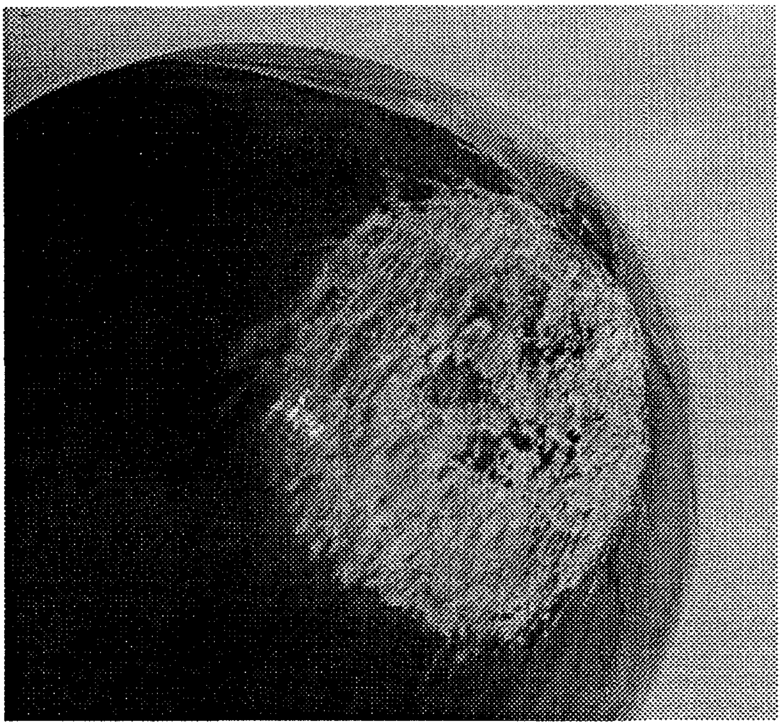


Photo 4 : One of the bullet holes in the cylinder in test n°4



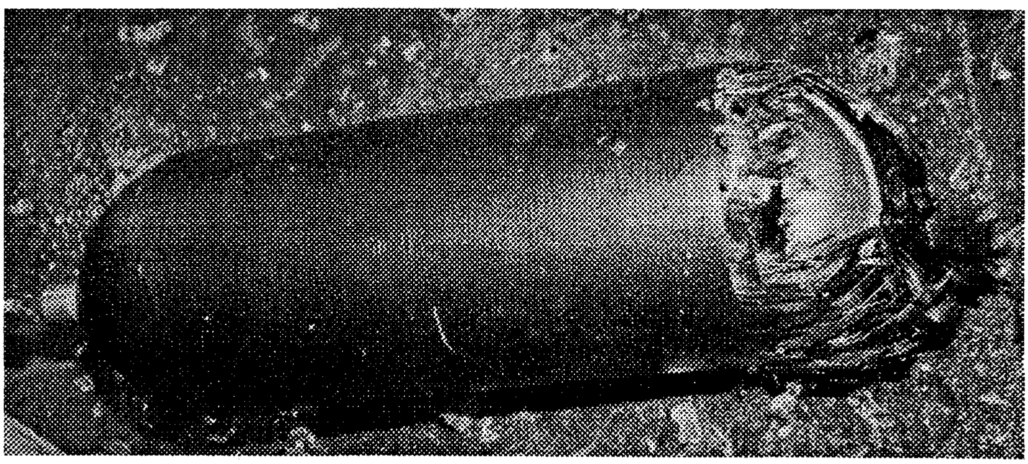


Photo 5 : the bottom of the cylinder was severely damaged by the fall in test n°5 and the cylinder ruptured in the impact zone

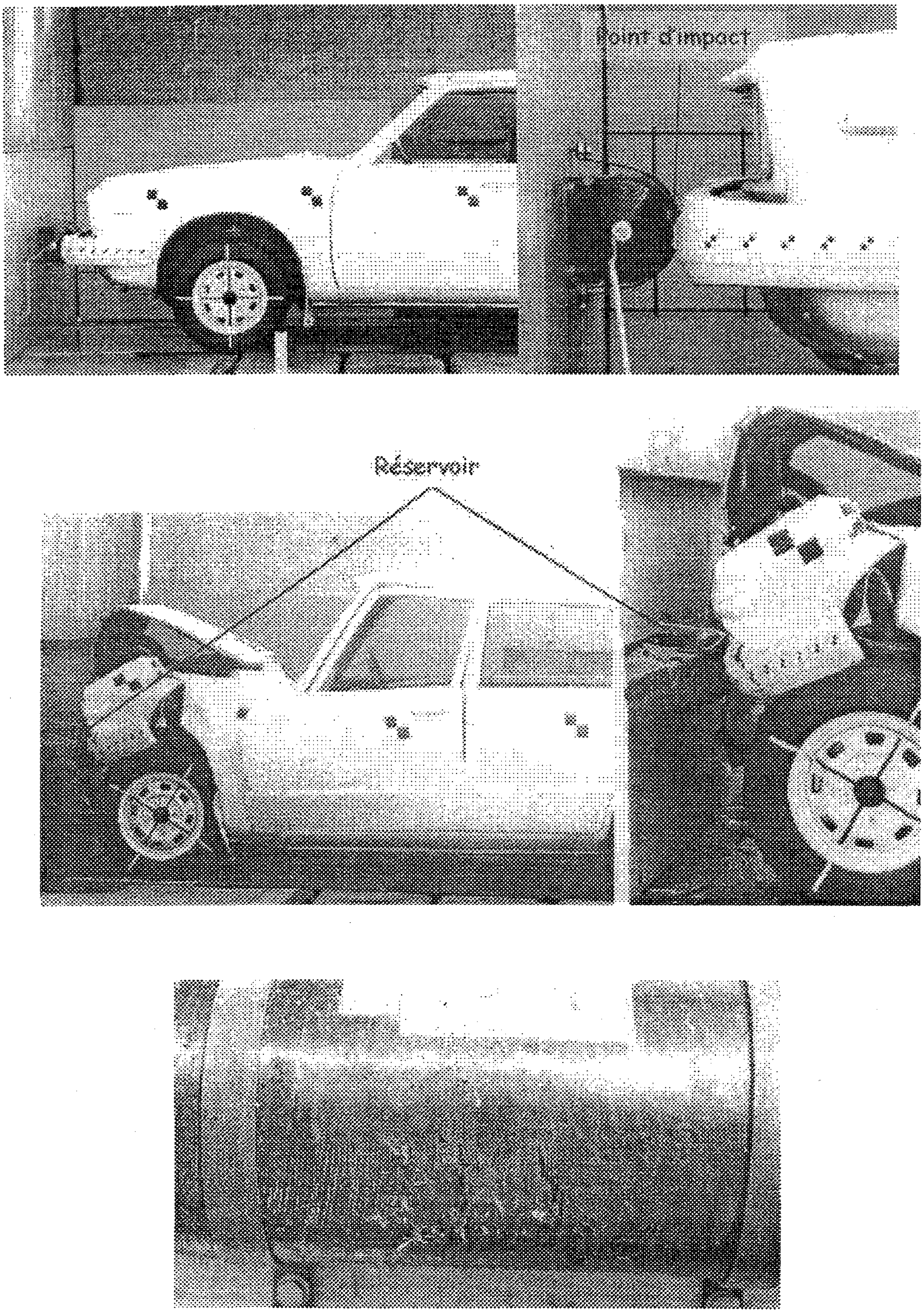


Photo 6 : the cylindrical wall of the bottle was slightly damaged by the crash test n°6